

Giant Magnetoresistance Oscillations Induced by Microwave Radiation and a Zero-Resistance State in a 2D Electron System with a Moderate Mobility

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The effect of a microwave field in the frequency range from 54 to 140 GHz on the magnetotransport in a GaAs quantum well with AlAs/GaAs superlattice barriers and with an electron mobility no higher than $10^6 \text{ cm}^2/\text{Vs}$ is investigated. In the given two-dimensional system under the effect of microwave radiation, giant resistance oscillations are observed with their positions in magnetic field being determined by the ratio of the radiation frequency to the cyclotron frequency. Earlier, such oscillations had only been observed in GaAs/AlGaAs heterostructures with much higher mobilities. When the samples under study are irradiated with a 140-GHz microwave field, the resistance corresponding to the main oscillation minimum, which occurs near the cyclotron resonance, appears to be close to zero. The results of the study suggest that a mobility value lower than $10^6 \text{ cm}^2/\text{Vs}$ does not prevent the formation of zero-resistance states in magnetic field in a two-dimensional system under the effect of microwave radiation.

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Current interest in studying the transport in two-dimensional (2D) electron systems is related to the recent observation of resistance oscillations in magnetic field that arise in high-mobility GaAs/AlGaAs heterostructures under the effect of microwave radiation [1]. It was found that these oscillations are periodic in the inverse magnetic field ($1/B$) with a period determined by the ratio of the microwave radiation frequency to the cyclotron frequency. The photoresponse oscillations in magnetic field in a high-mobility 2D system (such oscillations were predicted more than 30 years ago [2]) fundamentally differed from the behavior of photoresponse in GaAs/AlGaAs heterostructures with lower mobilities [3]. The effect of microwave radiation on the magnetotransport in GaAs/AlGaAs heterostructures of moderate quality was found to manifest itself as a photoresistance peak caused by the heating of the 2D electron gas under the magnetoplasma resonance conditions [4]. Soon after the first experimental observation of the microwave radiation-induced resistance oscillations in magnetic field in high-mobility GaAs/AlGaAs heterostructures, it was shown that the minima of these oscillations may correspond to resistance values close to zero [5, 6, 7].

This unexpected experimental result initiated intensive theoretical studies of the aforementioned phenomenon [7, 8, 9, 10, 11, 12, 13, 14, 15, 16]. However, despite the multitude of theoretical publications, the mechanisms responsible for the resistance oscillations under the effect of a microwave field in 2D systems with large filling factors remain open to discussion. The role of the mobility of charge carriers in the manifestation of microwave-induced zero-resistance states arising in magnetic field in 2D systems also remains unclear. It is commonly believed that the mobility should exceed $3 \times 10^6 \text{ cm}^2/\text{Vs}$

[17]. As for the experimental studies of the photoreponse to microwave radiation in 2D systems in classically strong magnetic fields, such studies, excluding a few of them [17, 18, 19, 20], are restricted to high-mobility GaAs/AlGaAs heterostructures with thick spacers and, hence, low electron concentrations [21, 22, 23].

In this paper, we report on the observation of resistance oscillations periodic in the inverse magnetic field that arise under the effect of irradiation with millimetric waves in GaAs quantum wells with a much lower mobility and a much higher concentration of 2D electrons, as compared to those reported earlier in [1, 5, 6, 7]. We experimentally demonstrate that, despite the relatively low mobility, in the 2D system under study at the temperature $T = 1.7 \text{ K}$, the effect of microwave radiation at the frequency $F = 140 \text{ GHz}$ gives rise to a close-to-zero resistance state in magnetic field.

We studied heterostructures with modulated doping, which represented GaAs quantum wells with AlAs/GaAs superlattice barriers [18, 18, 20]. The width of a GaAs quantum well was 13 nm. The structures were grown by molecular beam epitaxy on GaAs substrates. After a short-period illumination by a red light-emitting diode, the concentration and mobility of 2D electrons in our samples were $n_e = 8.5 \times 10^{11} \text{ cm}^{-2}$ and $\mu = 560 \times 10^3 \text{ cm}^2/\text{Vs}$, respectively. The measurements were carried out at temperatures of 1.7 and 4.2 K in magnetic fields B up to 0.6 T. We used Hall bars with a width of $50 \text{ }\mu\text{m}$ and a spacing of $250 \text{ }\mu\text{m}$ between the potential contact pads. The microwave radiation was supplied to the sample via a circular waveguide with an inner diameter of 6 mm. The output microwave power of the generators used in the experiment was $P_{\text{out}} = (4-10) \text{ mW}$. The resistance was measured using an alternating current of

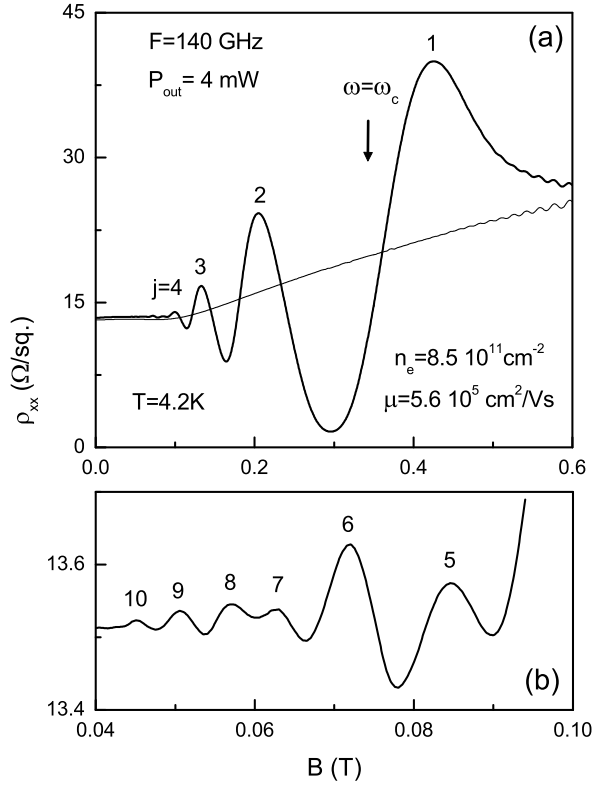


FIG. 1: (a) Experimental $\rho_{xx}(B)$ dependences for the 2D electron gas in a GaAs quantum well with AlAs/GaAs superlattice barriers at $T = 4.2$ K (the thin line) in the absence and (the thick line) in the presence of 140-GHz microwave radiation. (b) A detailed $\rho_{xx}(B)$ dependence in the presence of microwave radiation in magnetic fields below 0.1 T. The arrow indicates the position of the cyclotron resonance. The ordinal numbers of maxima are indicated near them beginning from the main maximum.

$(1-10) \times 10^{-7}$ A with a frequency of (0.3–1) kHz.

Figure 1 shows the $\rho_{xx}(B)$ dependences in the absence of microwave radiation and in the presence of radiation at a frequency of 140 GHz at a temperature of 4.2 K. One can see that the microwave radiation causes giant oscillations of magnetoresistance. An analysis of the positions of the first four maxima of these oscillations shows that they are periodic in inverse magnetic field. However, the positions of the maxima with numbers 5–10 deviate from the linear dependence on inverse magnetic field. A qualitatively similar behavior was observed earlier for high-mobility GaAs/AlGaAs heterostructures with a much smaller concentration [6] and was explained by the spin splitting [24]. One also can clearly distinguish specific points where the microwave radiation does not affect the resistance of the 2D electron gas. One of such points is indicated by the arrow in the plot and corresponds to the condition $\omega = \omega_c$, where ω is the microwave radiation frequency and ω_c is the cyclotron frequency. The minimum that is closest to this point is the deepest of all

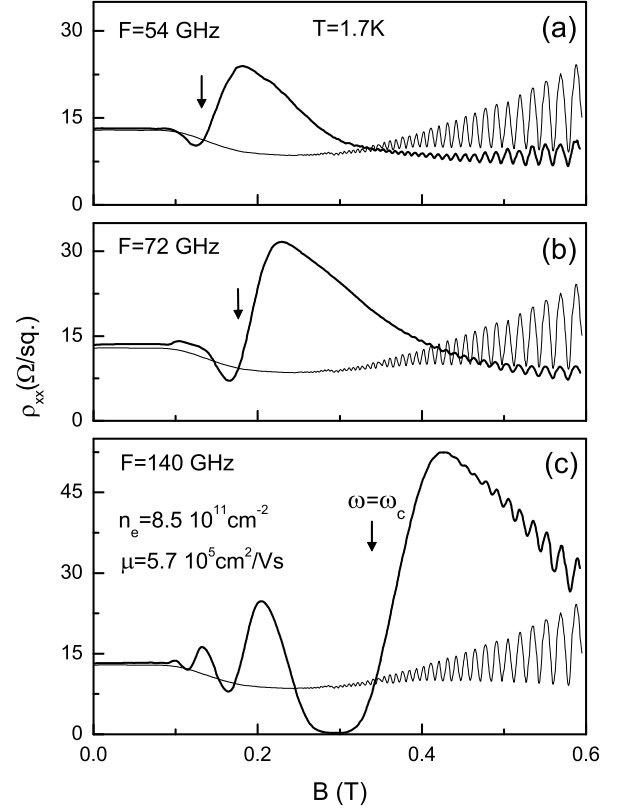


FIG. 2: Experimental $\rho_{xx}(B)$ dependences for the 2D electron gas in a GaAs quantum well with AlAs/GaAs superlattice barriers at $T = 1.7$ K (the thin line) in the absence and (the thick line) in the presence of microwave radiation with the frequencies $F =$ (a) 54, (b) 72, and (c) 140 GHz. The arrows indicate the positions of the cyclotron resonance.

the minima in the plot.

Figure 2 illustrates the effect of microwave radiation on the magnetoresistance of 2D electron gas in a GaAs quantum well with AlAs/GaAs superlattice barriers at a temperature of 1.7 K for three different microwave frequencies: 54, 72, and 140 GHz. The experimental dependences presented in this figure show that the point of intersection of the curves that corresponds to the cyclotron resonance position is shifted in magnetic field as the frequency varies. In addition, one can see that, at the microwave frequency $F = 140$ GHz and a temperature of 1.7 K, the resistance corresponding to the main minimum located near the aforementioned point takes a value close to zero.

It should be noted that, when the temperature is lowered from 4.2 to 1.7 K, the $\rho_{xx}(B)$ dependence observed in the absence of microwave radiation considerably changes in appearance. On the one hand, the Shubnikov-de Haas oscillation amplitude increases, and, on the other hand, the positive magnetoresistance typical of the given heterostructures at $T = 4.2$ K changes to negative magnetoresistance at $T = 1.7$ K. An analysis of the ex-

perimental data shows that the negative magnetoresistance that appears at the lower temperature is not described by a quadratic dependence on B : it exhibits a “shelf” near $B = 0$ and, hence, cannot be caused by the electron-electron interaction alone [25]. Therefore, we believe that the negative magnetoresistance observed in our structures in classically strong magnetic fields should be qualitatively explained as the result of a combined effect produced on the transport processes by the electron-electron interaction and the classical “memory” effects [26, 27, 28].

For identification of the resistance oscillations induced by microwave radiation, it is necessary to determine the positions of the specific points of these oscillations on the B axis at a fixed frequency ω , i.e., the positions of maxima, minima, and points where the photoresponse is absent. Most of the theoretical publications allow an exact determination of positions for only those points where the resistance is unaffected by microwave radiation. The positions of these points correspond to the cyclotron resonance and its harmonics $\omega = n\omega_c$, where n is a positive integer number. This theoretical result agrees well with the experimental data [29], which suggest that the most accurately determined point of resistance oscillations in magnetic field is the point corresponding to the cyclotron resonance. This point lies between the main maximum and the main minimum, at the intersection of the $\rho_{xx}(B)$ dependences obtained in the absence and in the presence of microwave radiation.

Such an intersection is observed in our dependences. From the analysis of our experimental data, it follows that the position of the intersection is shifted in magnetic field with varying frequency in accordance with the displacement of the cyclotron resonance position calculated by using the effective electron mass in GaAs ($0.067m_0$). This fact suggests that the nature of oscillations presented in Figs. 1 and 2 and arising under the effect of microwave radiation in a GaAs quantum well with AlAs/GaAs superlattice barriers is the same as the nature of oscillations first observed in [1] and predicted in [2].

Note that, in our experimental dependences, unlike [6, 29], the point positioned near the cyclotron resonance and characterized by the absence of the effect of microwave radiation on the magnetoresistance of the 2D electron gas is shifted toward higher magnetic fields. From Figs. 1 and 2, one can see that, at a microwave frequency of 140 GHz, this shift is more pronounced for the curves obtained at 4.2 K. We believe that one of the possible reasons for such a shift is the error in determining the magnitude of the magnetic field component perpendicular to the surface of the 2D electron gas; in our experiments, this error could reach 10%. The problem of a precise position determination for the specific points of magnetoresistance oscillations induced by microwave radiation in 2D electron systems with moderate

mobility is still unsolved and will be the subject of our subsequent experimental studies.

Today, most of the theoretical concepts explaining the nature of these oscillations are based, on the one hand, on indirect optical transitions accompanied by a momentum variation due to the scattering by impurities or phonons [2, 9, 10, 11, 12] or, on the other hand, on the nonequilibrium filling of electron states at the broadened Landau levels [7, 14, 15]. On the basis of experimental data available to us by this day, we cannot decide between the theoretical scenarios to explain the oscillations arising in our samples under the effect of a microwave field of the millimetric wave range. However, we believe that one of the possible reasons for the manifestation of the close-to-zero resistance state that is induced by microwave radiation in GaAs quantum wells with moderate mobility and high concentration of 2D electrons is the elastic electron scattering by rough heteroboundaries with participation of photons. This hypothesis is consistent with the role that is played by the heteroboundaries of a GaAs quantum well with AlAs/GaAs superlattice barriers in the manifestation of magnetophonon resonance in this well [30].

Thus, we showed that, with an increase in the concentration of the 2D electron gas, the zero-resistance states induced by microwave radiation manifest themselves in GaAs quantum wells with AlAs/GaAs superlattice barriers for moderate mobility values. The experimental data obtained by us make it possible to shift the experimental studies of the nature of zero-resistance states induced by electromagnetic field in 2D electron systems to the submillimetric wave range and to develop receivers for infrared radiation on the basis of this effect.

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